IGM Tomography meeting (Aug. 29-31, 2016)

Resolving the Clumpy Structure of the Outflow Winds in Gravitationally Lensed Quasar

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TM et al., 2013, AJ, 145, 48
TM et al., 2014, ApJL, 794, 20
TM et al., 2016, ApJ, 825, 25

OUTLINE

Background

- Classification of Quasar absorption lines
- Quasar outflow & Accretion disk-wind model
- Unresolved internal structure of the outflow wind

Our strategy & Observations

- Gravitationally lensed quasar, SDSS J1029+2623
- R~30,000 spectroscopy with Subaru + HDS, VLT + UVES

Results & Discussion

- Intrinsic or intervening absorption?   (TM et al. 2013)
- Multi-sightline or time variation?   (TM et al. 2014)
- Origin of Narrow Absorption Lines?
- Global picture of the outflow?   (TM et al. 2016)

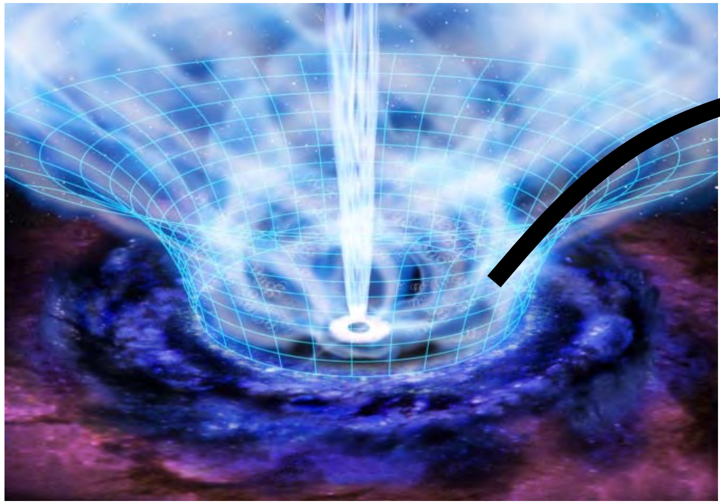
Background

IGM
chemical evolution

host galaxy
chemical evolution
star formation rate

metal pollution
co-evolution

outflow



energy
angular momentum
heavy elements

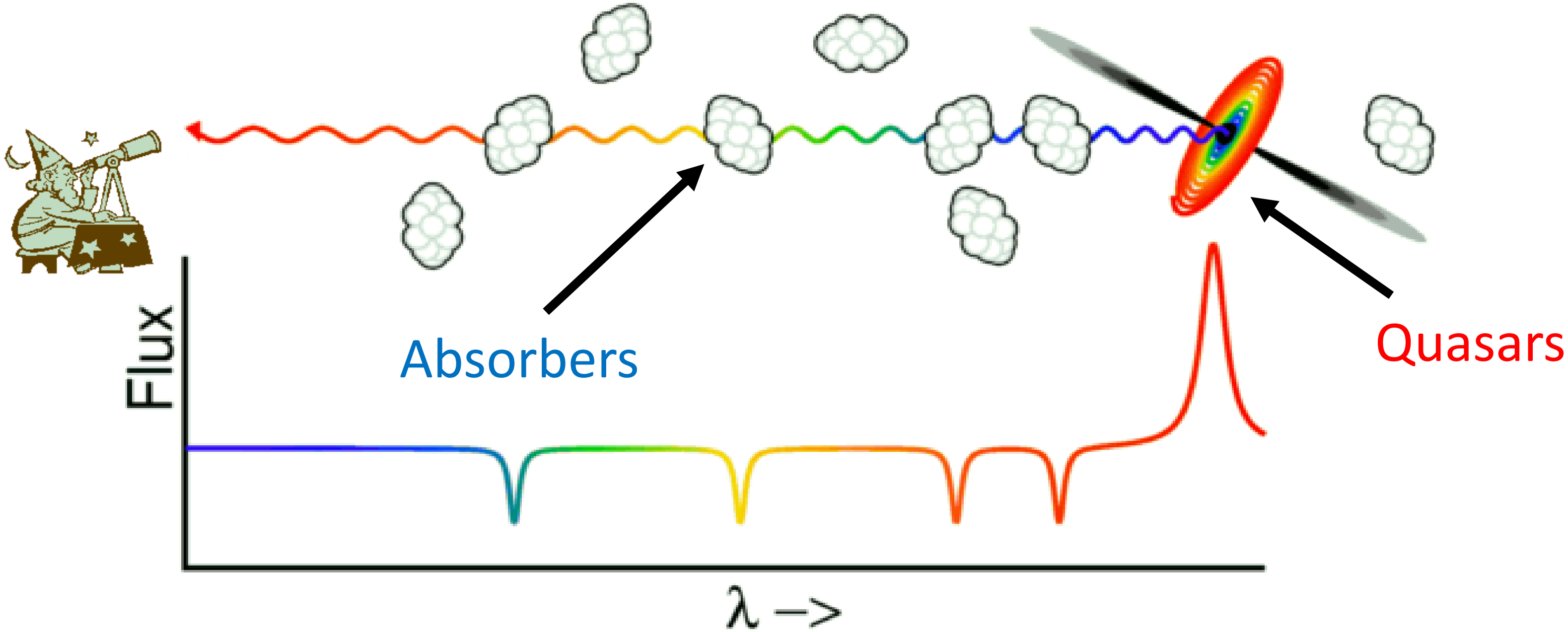
detected as absorption lines

acceleration
gas accretion

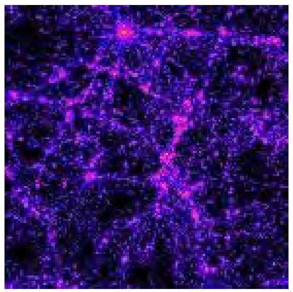
accretion disk
Quasar activity
(e.g., mass accretion rate, variation, luminosity)

Quasar Absorption Lines (QALs)

Absorption features in spectra of background quasars that are produced by absorbers along the observed sight-lines.



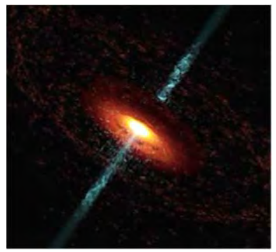
Our Galaxy



IGM

galaxies

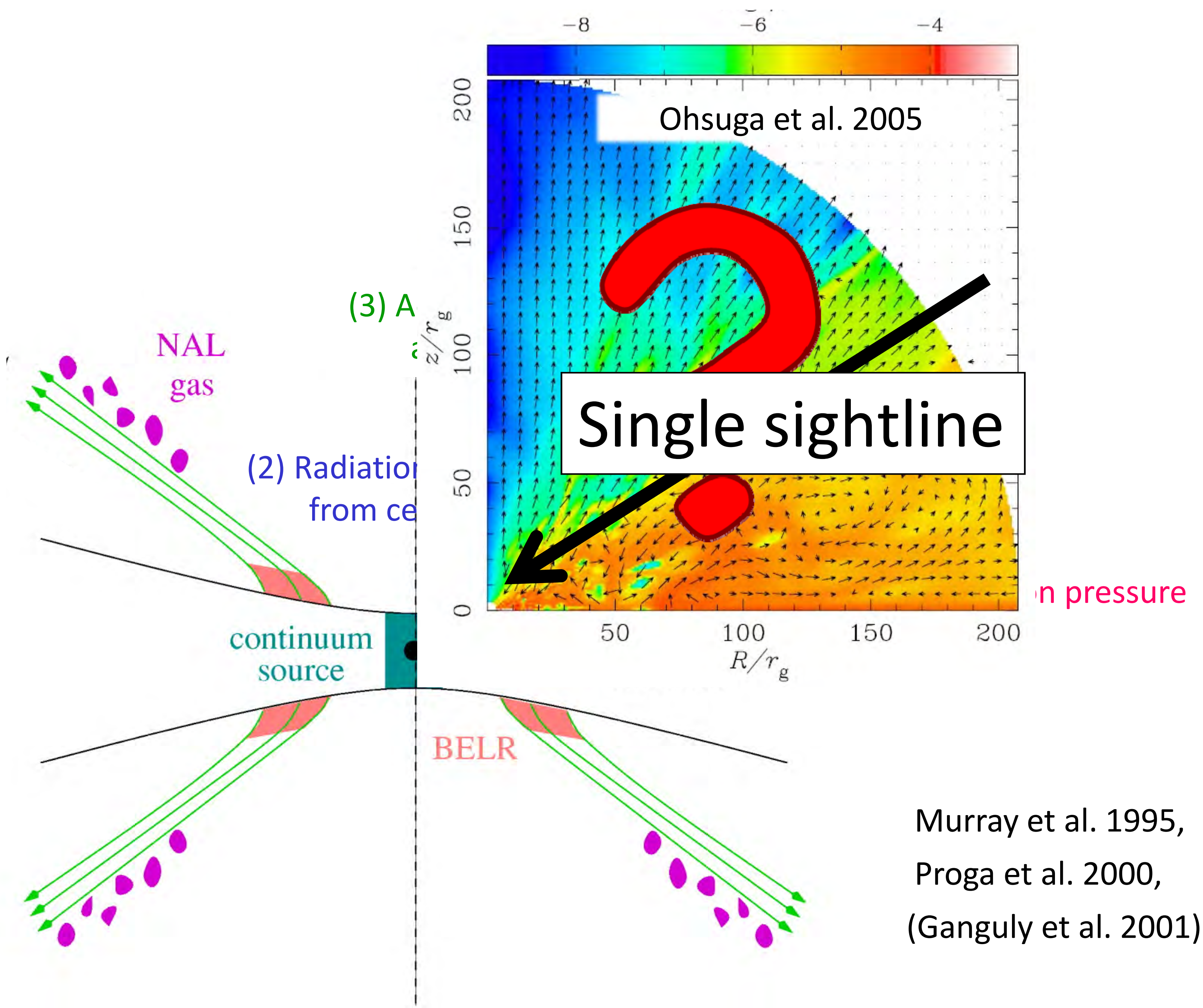
Intervening abs.



quasars

Intrinsic abs.

Accretion Disk-Wind Model



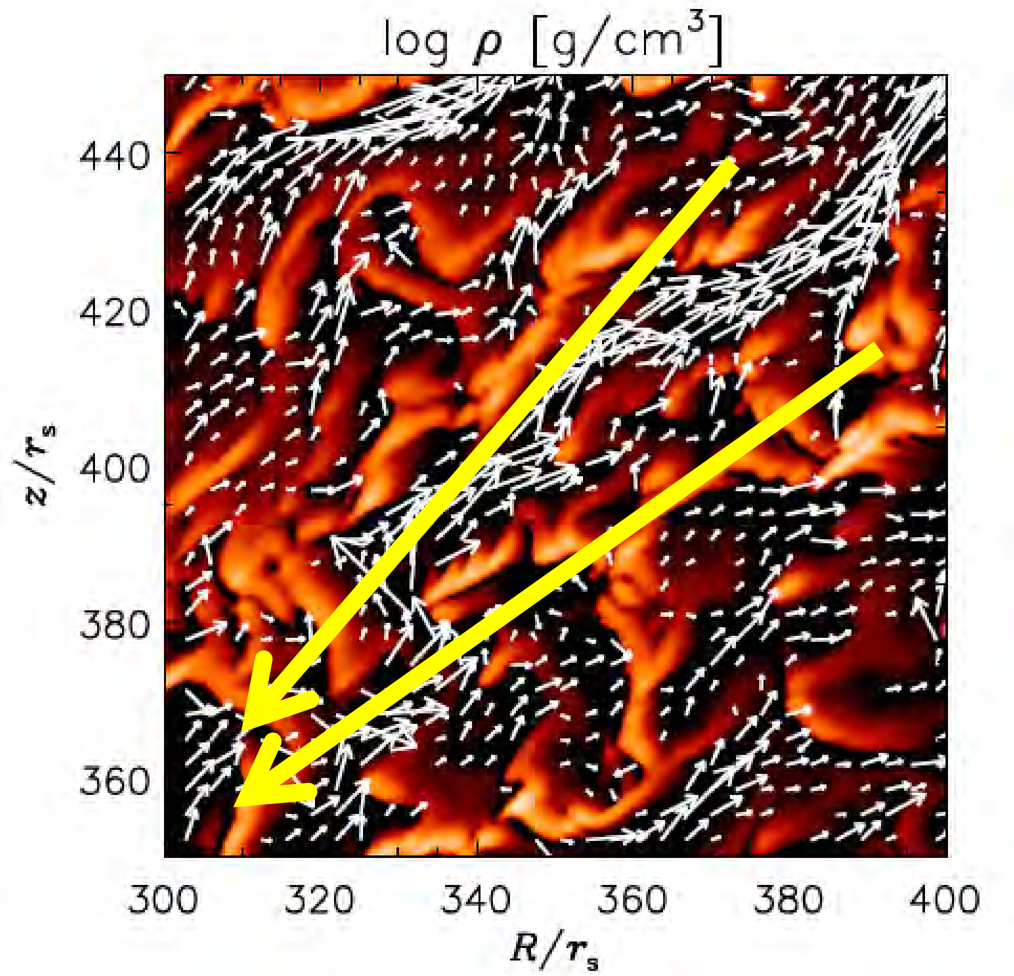
Murray et al. 1995,

Proga et al. 2000,

(Ganguly et al. 2001)

Complex Internal Structure?

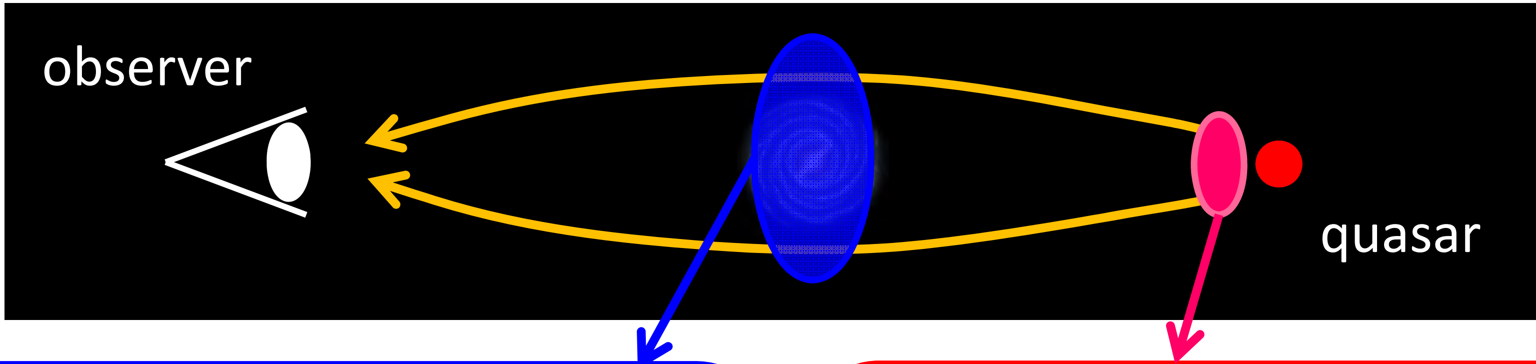
The outflow stream may have complex internal structure that consist of a number of small clumpy clouds ($\leq 10^{-3}$ pc) with very high gas densities ($n_e \geq 10^7$ cm^{-3}).



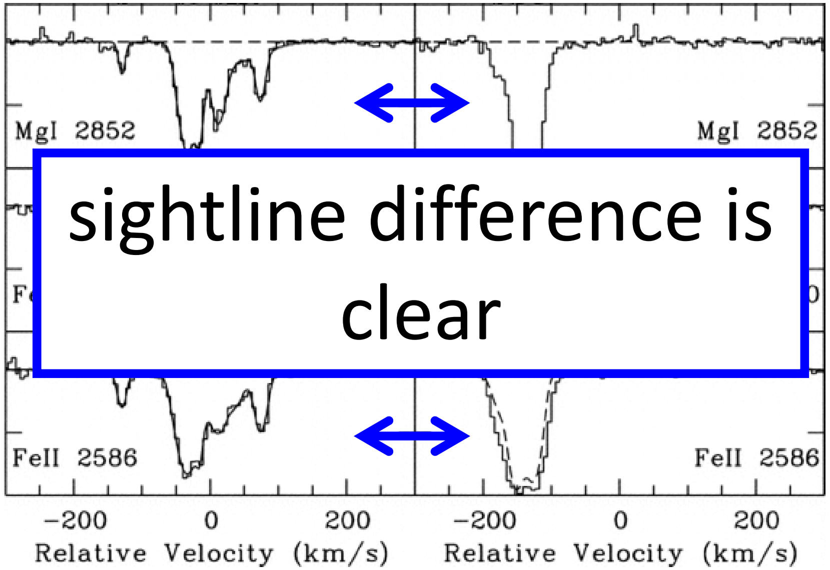
A radiation-MHD simulation by Takeuchi et al. (2013).

Our strategy & Observations

Multi-sightline spectroscopy



Foreground galaxy (DLA at z~0.93)
HE0512-3329 (z_{em} ~ 1.58)

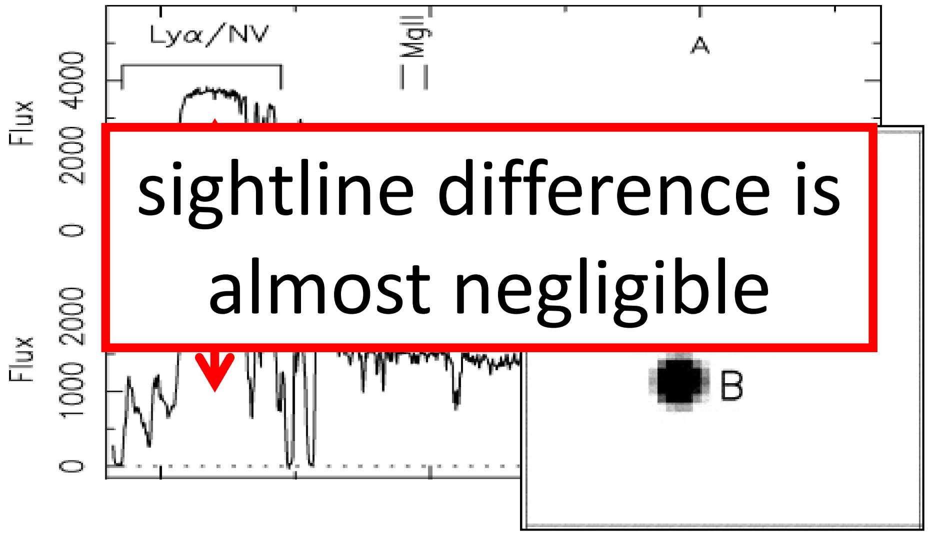


sightline difference is clear

θ ~0.64″ → d ~5 kpc

Lopez et al. (2005)

Outflow wind (BAL at z~3.9)
APM08279+5255 (z_{em} ~ 3.911)

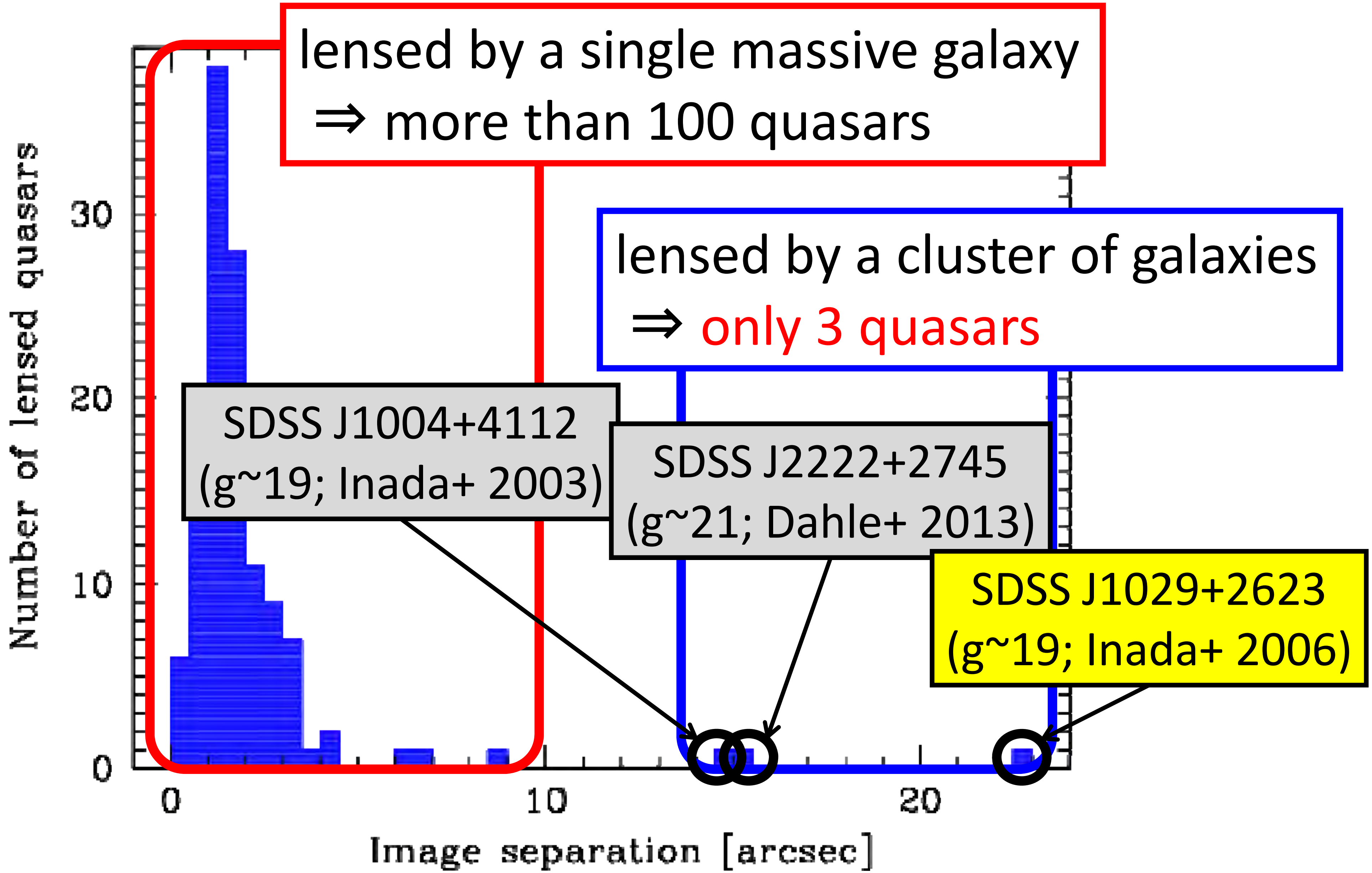


sightline difference is almost negligible

θ ~0.38″ → d ~ 10^{-4} pc (r~0.1kpc)

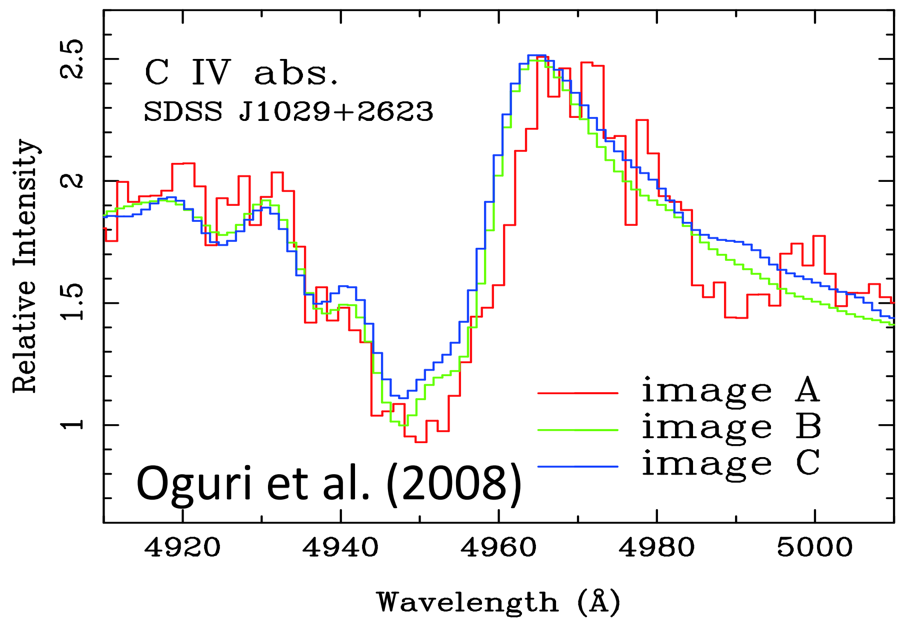
Lewis et al. (2002)

Lensed quasars discovered so far



Our target: SDSS J1029+2623

- Gravitationally lensed quasar at z_{em}~2.197 with three lensed images, A (m_V~18.72), B (~18.67), and C (~20.63).
- Lensed by a cluster of galaxies at z_L~0.58.
- The largest separation angle of θ~22".5 discovered so far (Inada+ 2006). [θ'~14".6 seen from the quasar]
- Strong absorption features on the blue wings of emission lines (i.e., P-Cygni profile) as candidates for intrinsic absorption lines.



Oguri et al. (2008)

Observations

We performed high-resolution spectroscopy (R~30,000) of the brightest two images of the quasar (images A & B) with Subaru/HDS in 2010/02 (E1) and 2014/04 (E3) and VLT/UVES in 2014/02 (E2).

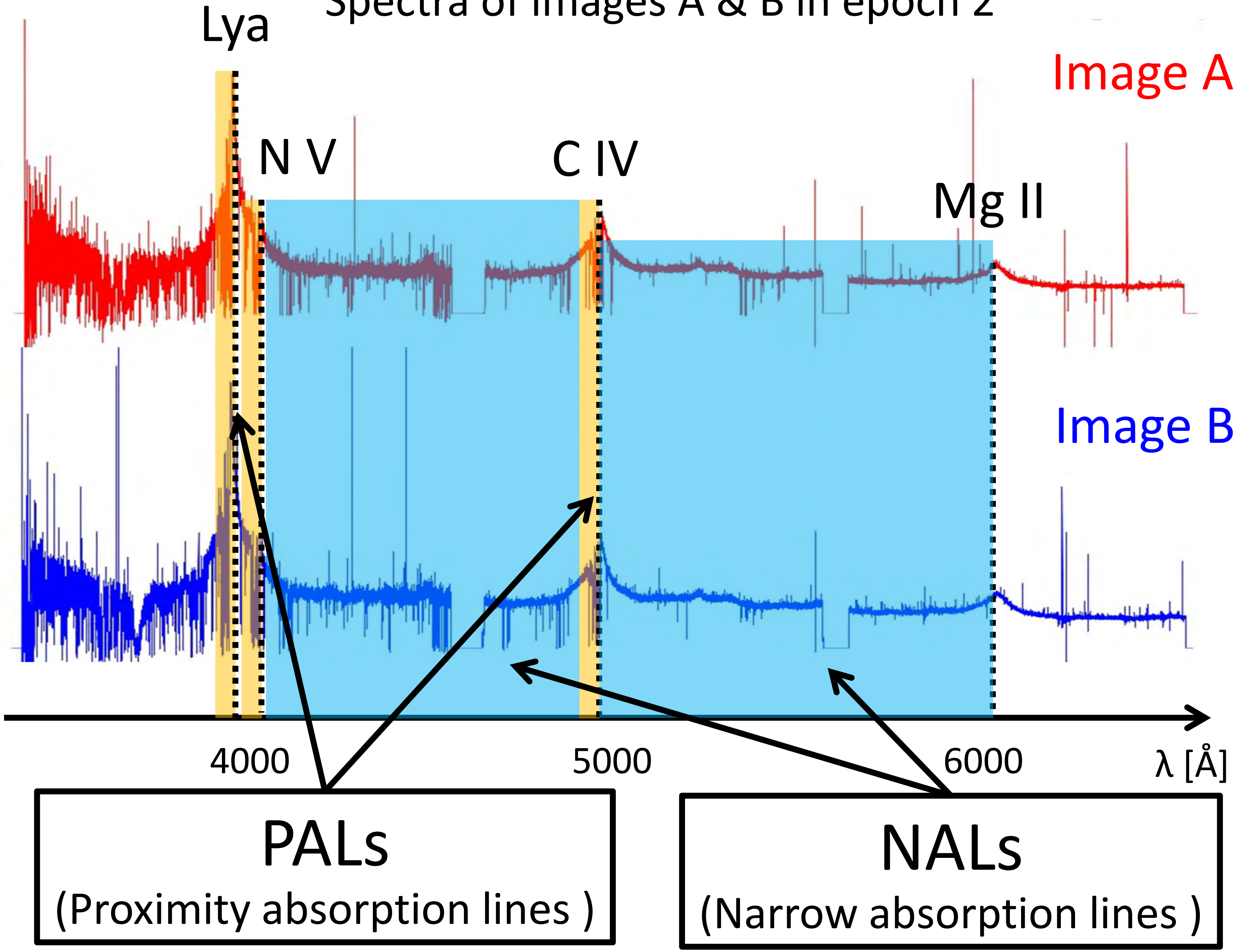
Target (1)	Obs Date (2)	Instrument (3)	R (4)	T_{exp} (sec) (5)	S/N[a] (pix^{-1}) (6)	Epoch
SDSS J1029+2623 A	2010 Feb 10	Subaru/HDS	30000	14400	13	E1
	2014 Jan 28 – Feb 3	VLT/UVES	33000	26670	23	E2
	2014 Apr 4	Subaru/HDS	36000	11400	14	E3
SDSS J1029+2623 B	2010 Feb 10	Subaru/HDS	30000	14200	13	E1
	2014 Feb 4 – 26	VLT/UVES	33000	26670	23	E2
	2014 Apr 4	Subaru/HDS	36000	11400	14	E3

~4yrs

~2mo.

Results & Discussion

Spectra of images A & B in epoch 2



- intrinsic or intervening absorption?

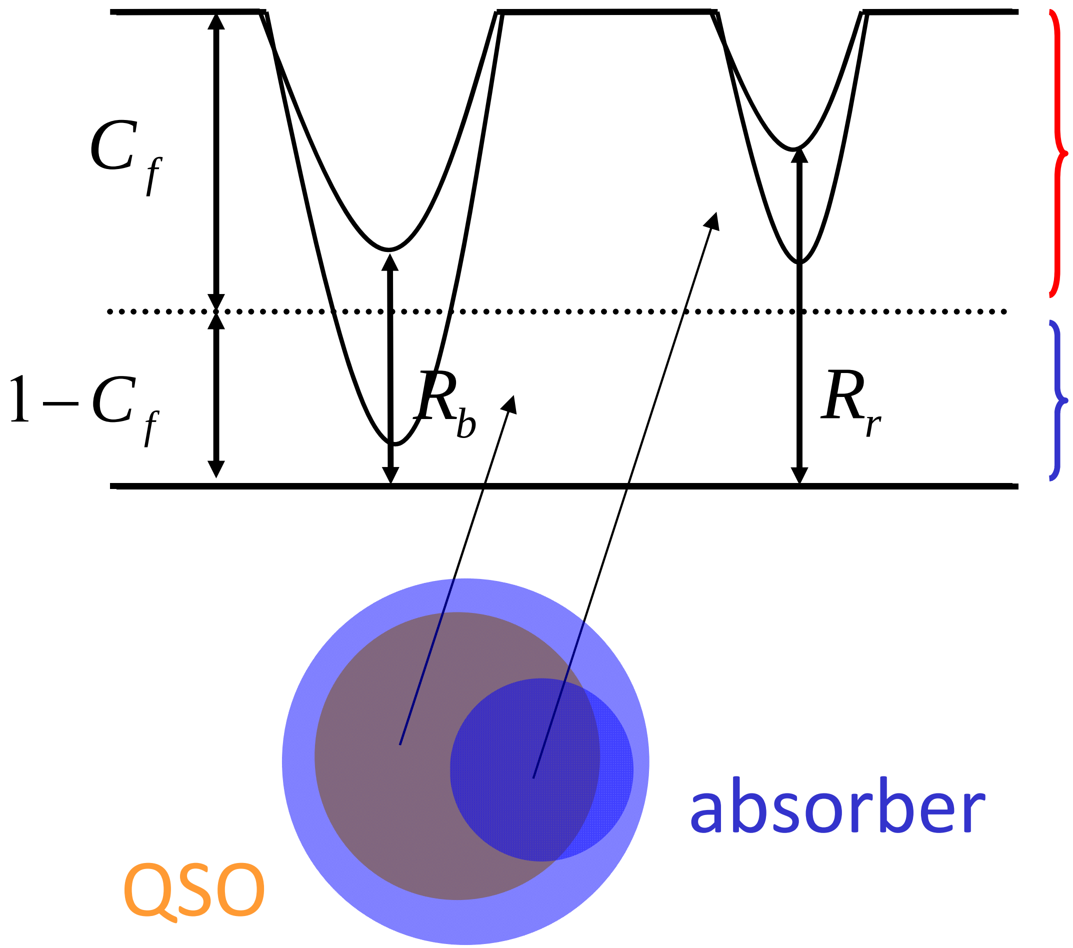
- multiple or single sightline?

- origin of narrow absorption lines?

- global picture of the outflow?

Partial Coverage Analysis

Dilution of absorption troughs by unocculted light from the quasar continuum source makes the optical depth ratio of resonant UV doublets (e.g., CIV, NV) deviate from 2:1, as dictated by atomic physics (e.g., Wampler et al. 1995).



$$R(\lambda) = C_f(\lambda) e^{-\tau(\lambda)} + [1 - C_f(\lambda)]$$

$$\tau \propto Nf\lambda$$

$$\left(\frac{R_r - 1 + C_f}{C_f} \right)^{f_b \lambda_b / f_r \lambda_r} = \frac{R_b - 1 + C_f}{C_f}$$

Covering factor

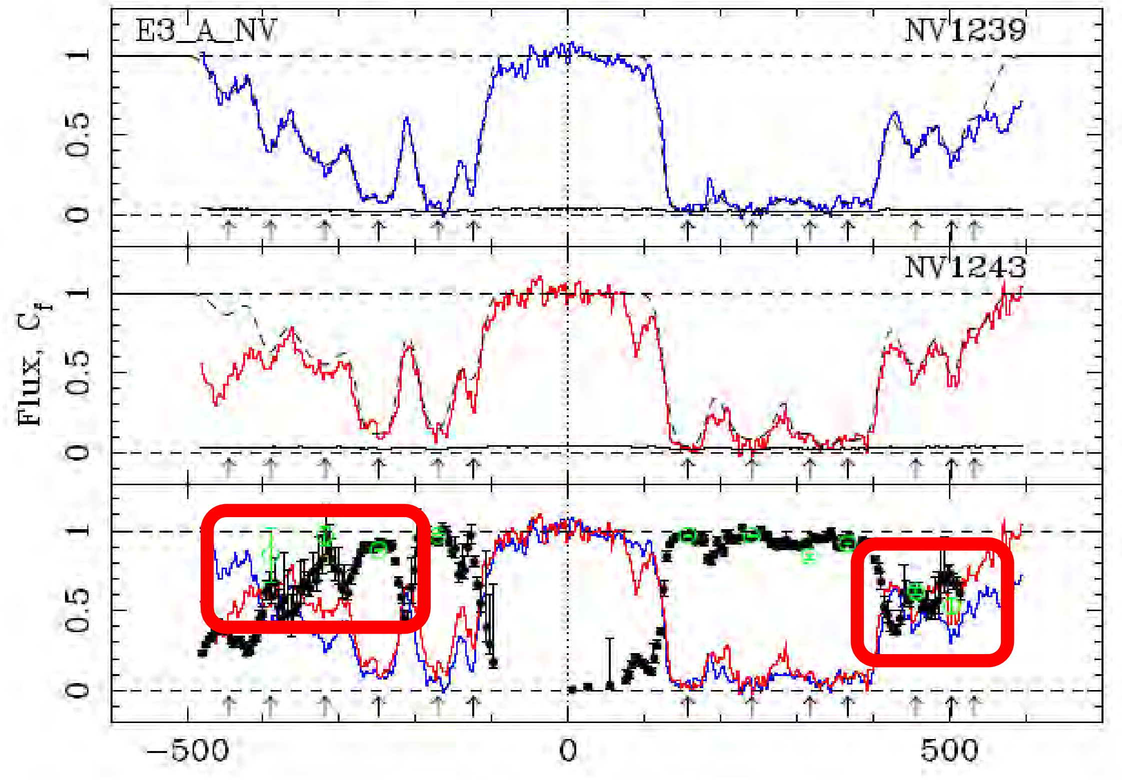
$$C_f = \frac{[R_r(v) - 1]^2}{R_b(v) - 2R_r(v) + 1}$$

(e.g., Wampler et al. 1995)

A sign of intrinsic line: Partial coverage

A substantial fraction of absorption components show partial coverage, which means the physical sizes of the absorbers are smaller than the background source.

N V PAL toward image A in epoch 2



N V 1239

N V1243

Covering factor
for each component (○)
or for each pixel (●)

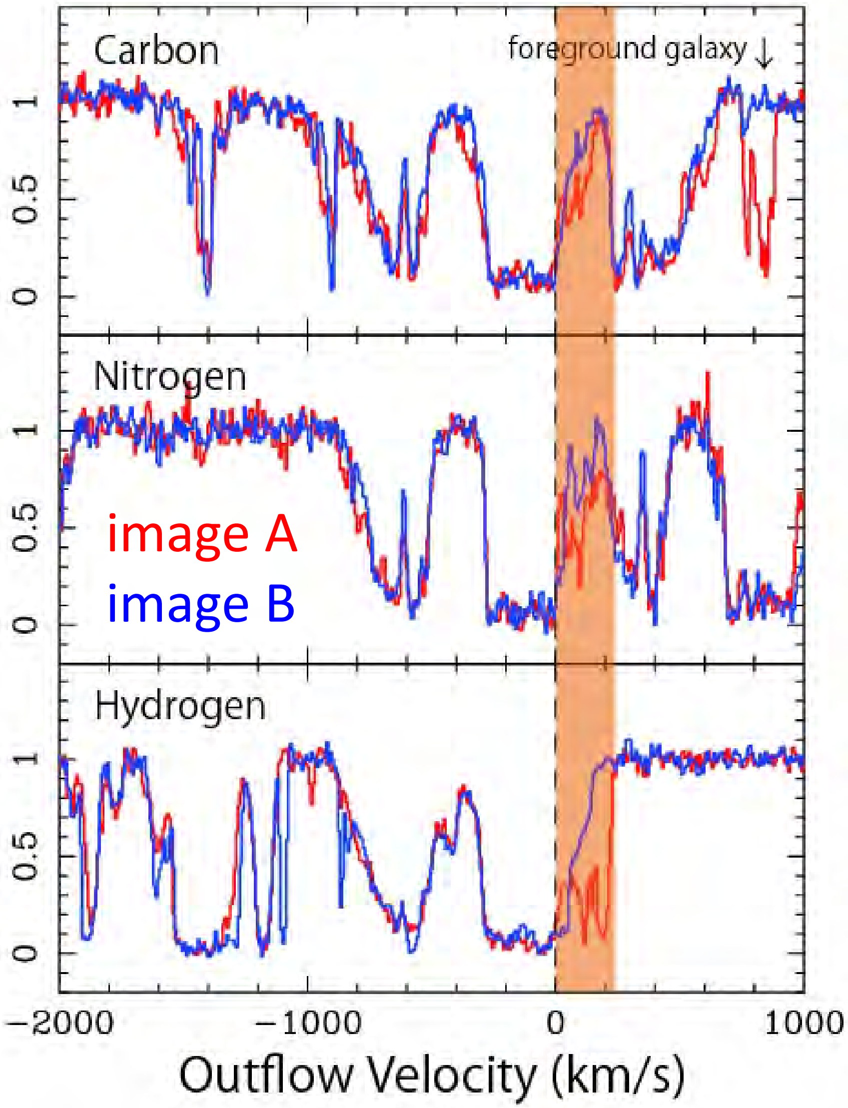
Relative velocity from the flux-weighted center, Δv (km/s)

Partial coverage suggests that the origin of PALs is indeed in the outflow gas (Misawa et al. 2013).

- intrinsic or intervening absorption?
- multiple or single-sightline?
- origin of narrow absorption lines?
- global picture of the outflow?

Difference in absorption profiles

PALs in epoch 1



A clear difference in absorption profile between the images A and B in the shaded area.

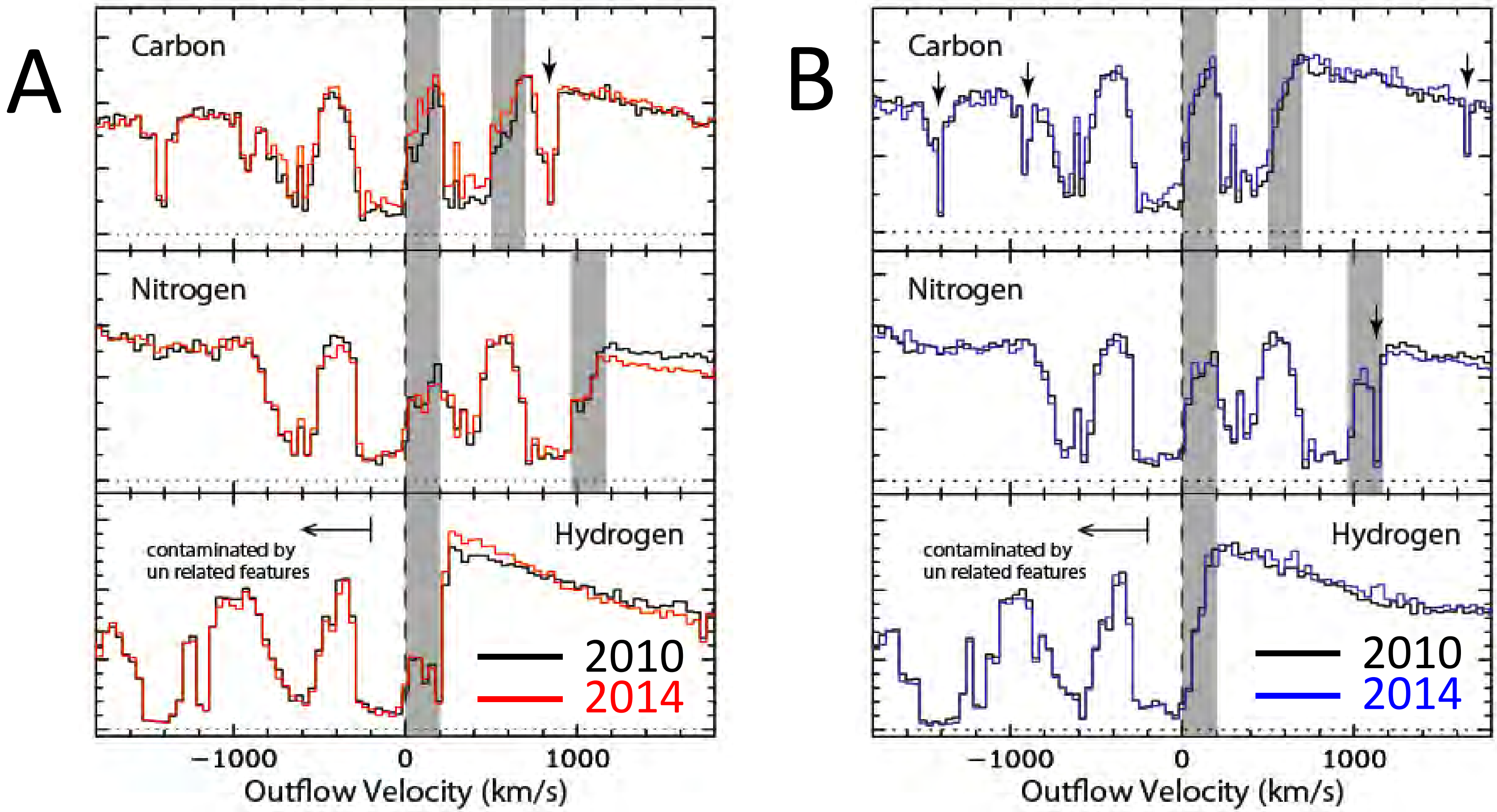
The likely scenarios include:

1. time-variability over time-delay of images A and B (Δt_{obs}~744d) (e.g., Chartas+ 2007)
2. difference in the absorption level along different sightlines (Chelouche 2003; Green 2006)

Confirming the multi-sightline scenario

The difference in absorption profiles has almost unchanged in Δt_{obs} > 744 days between epochs E1 and E3, implying the difference is not due to time variability, but due to differences along the sightlines (Misawa et al 2014).

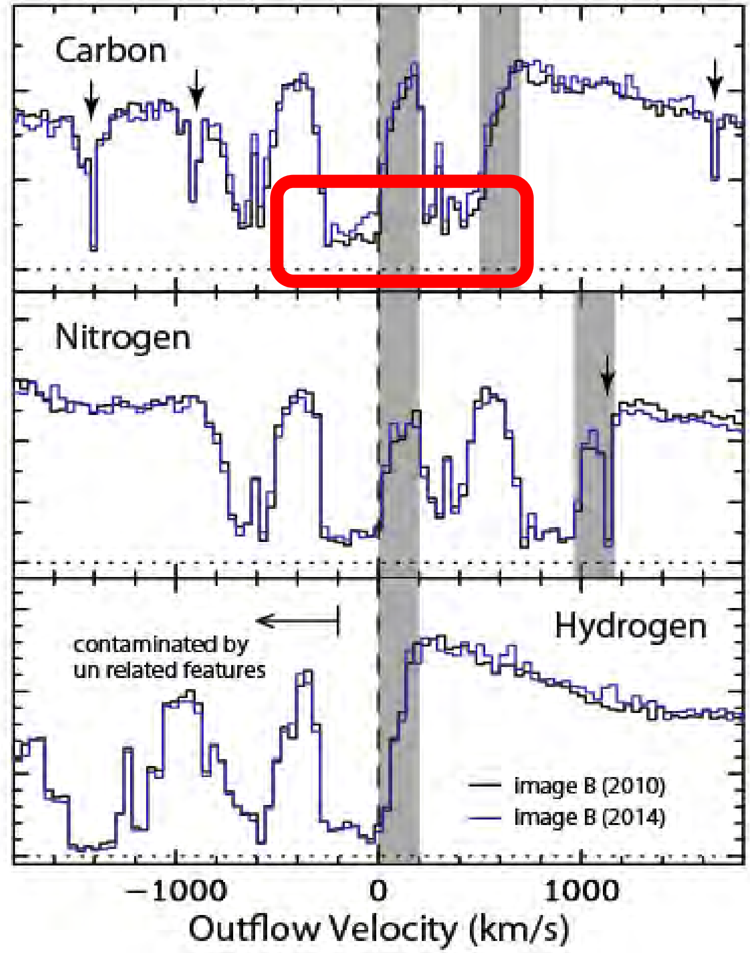
PALs toward image A (left) and B (right) in epochs 1 and 3



Time Variability in PALs

C IV PALs show a weak variability in their strength between epochs 1 and 3, which could be due to changes in the ionization state of the absorber.

PALs toward image B in E1 and E3



(a) ~~gas motion across our line of sight~~ (e.g., Gibson+ 2008; Muzahid+ 2015)

(b) change in the ionization state of the absorber (e.g., Hamann+ 2011)

$$n_e \approx \frac{1}{\alpha \cdot t_{rec}}$$ < 8.7x10^{3} cm^{-3}

$$r_{cloud} \approx \sqrt{\frac{1}{4\pi U n_e c}\int_0^{\lambda_{LL}} \frac{\lambda L_\lambda}{hc} d\lambda}$$

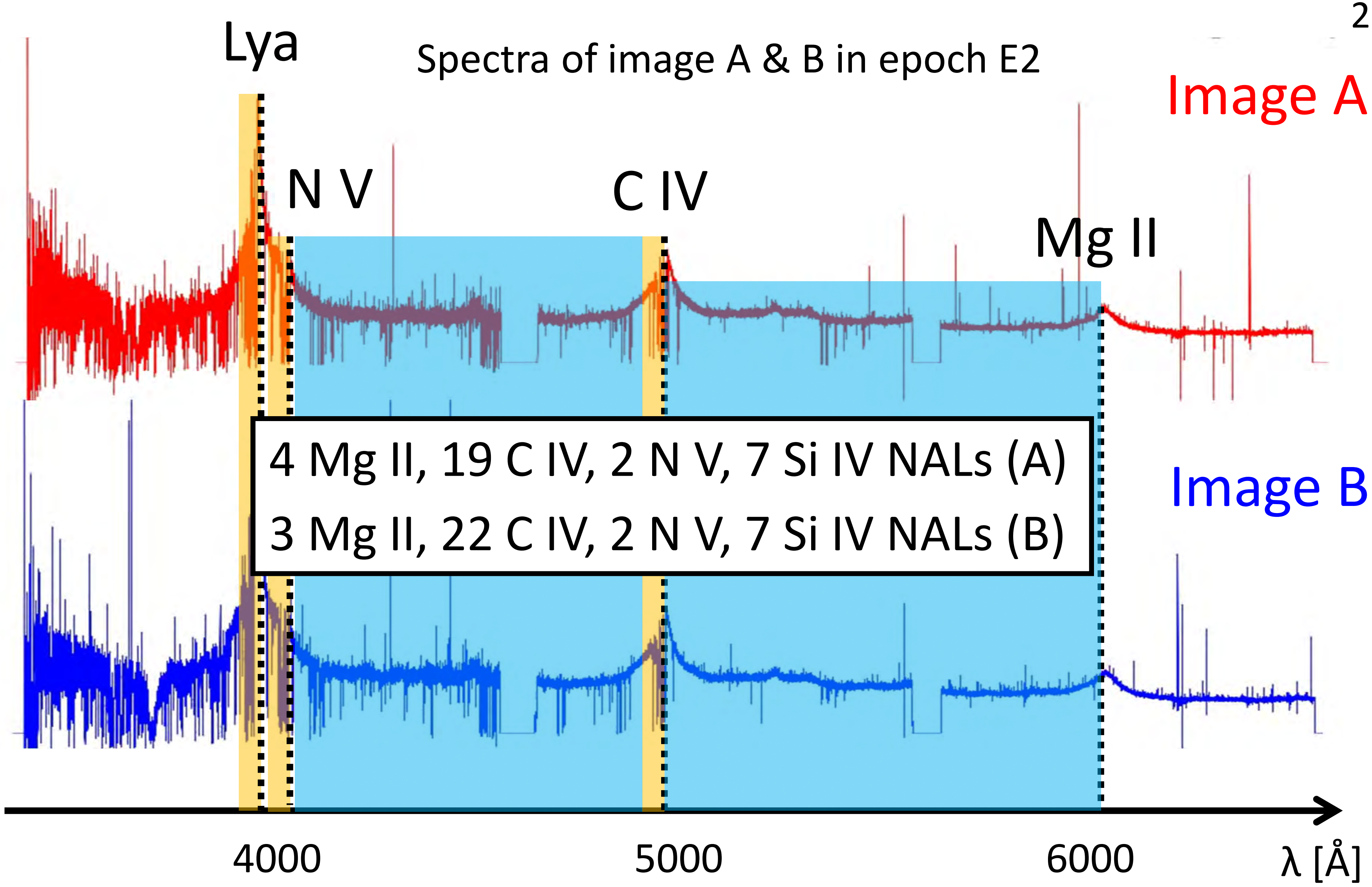
< 620 pc

- intrinsic or intervening absorption?

- multiple or single sightline?

- origin of narrow absorption lines?

- global picture of the outflow?

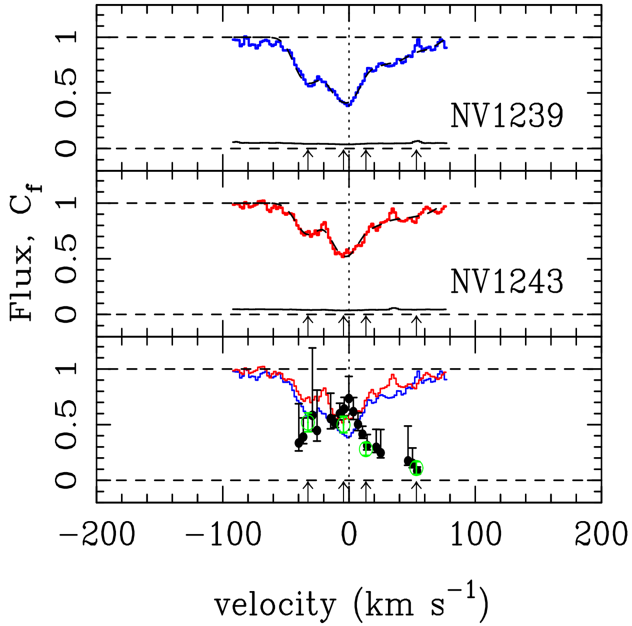


Absorption lines
- Proximity absorption lines (PALs)
- Narrow absorption lines (NALs)

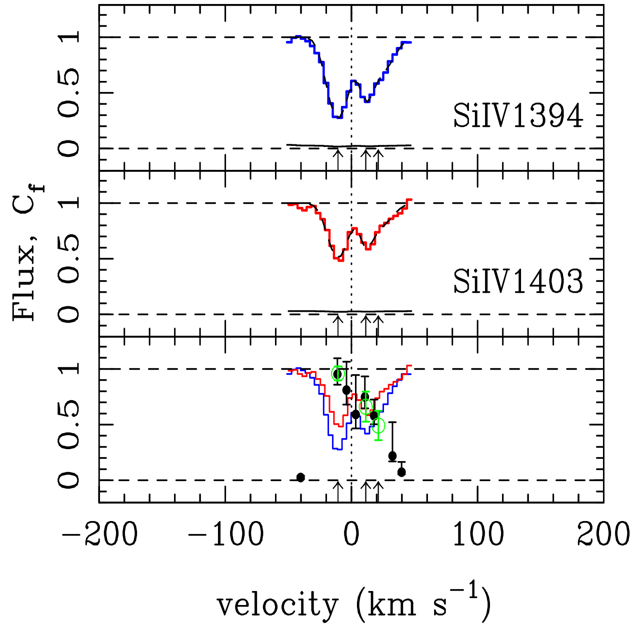
Partial coverage analysis for NALs

We separate all NALs into three classes (classes A, B, and C) according to the reliability that they are intrinsic NALs, based on the partial coverage analysis.

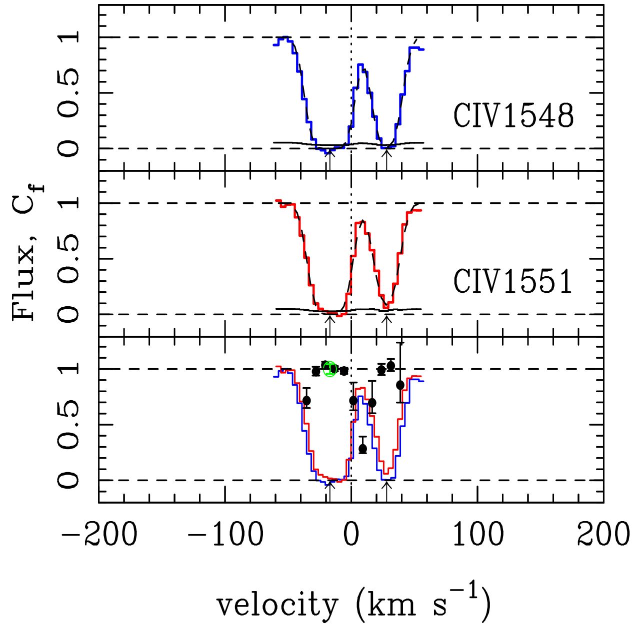
Class A
(reliable intrinsic)

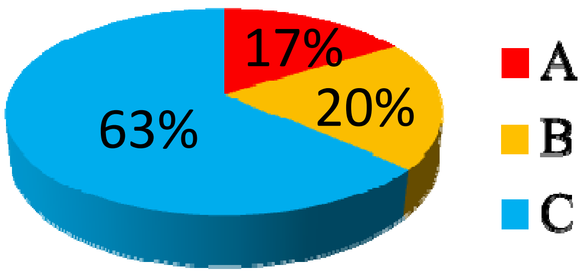


Class B
(possible intrinsic)



Class C
(intervening/unclassified)





11 class-A, 13 class-B, 42 class-C

(Image A & B in epoch E2)

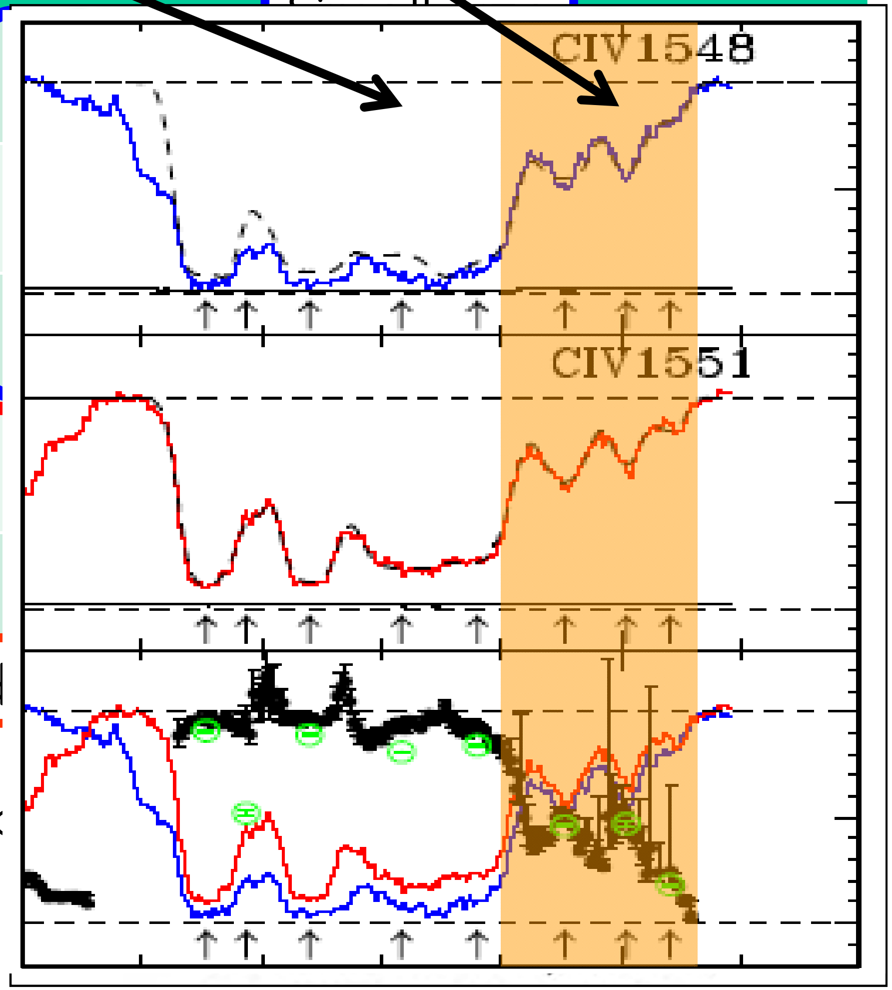
- intrinsic or intervening absorption?
- multiple or single sightline?
- origin of narrow absorption lines?
- global picture of the outflow?

Summary of PAL & intrinsic NAL absorbers

	PAL [a] (broad)	PAL [b] (narrow)	Intrinsic NAL
transverse size	> rθ		
covering factor	~ 1		
background source	BELR		
radial velocity	< 1000 km/s		
ionization condition	high		

Large size

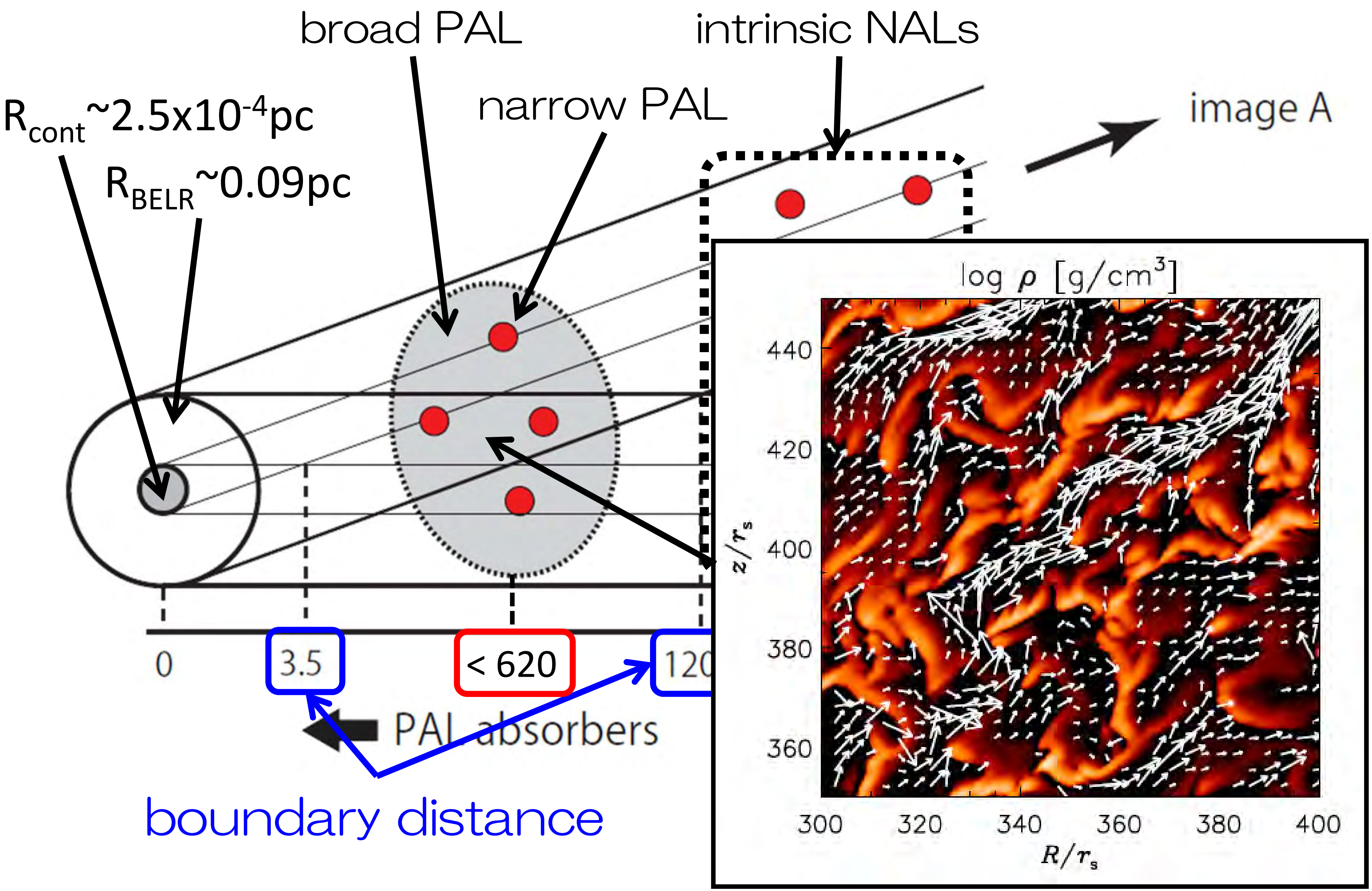
Small d



a: PALs with common absorption profiles in

b: PALs with sightline variation.

Possible internal structure of the outflow



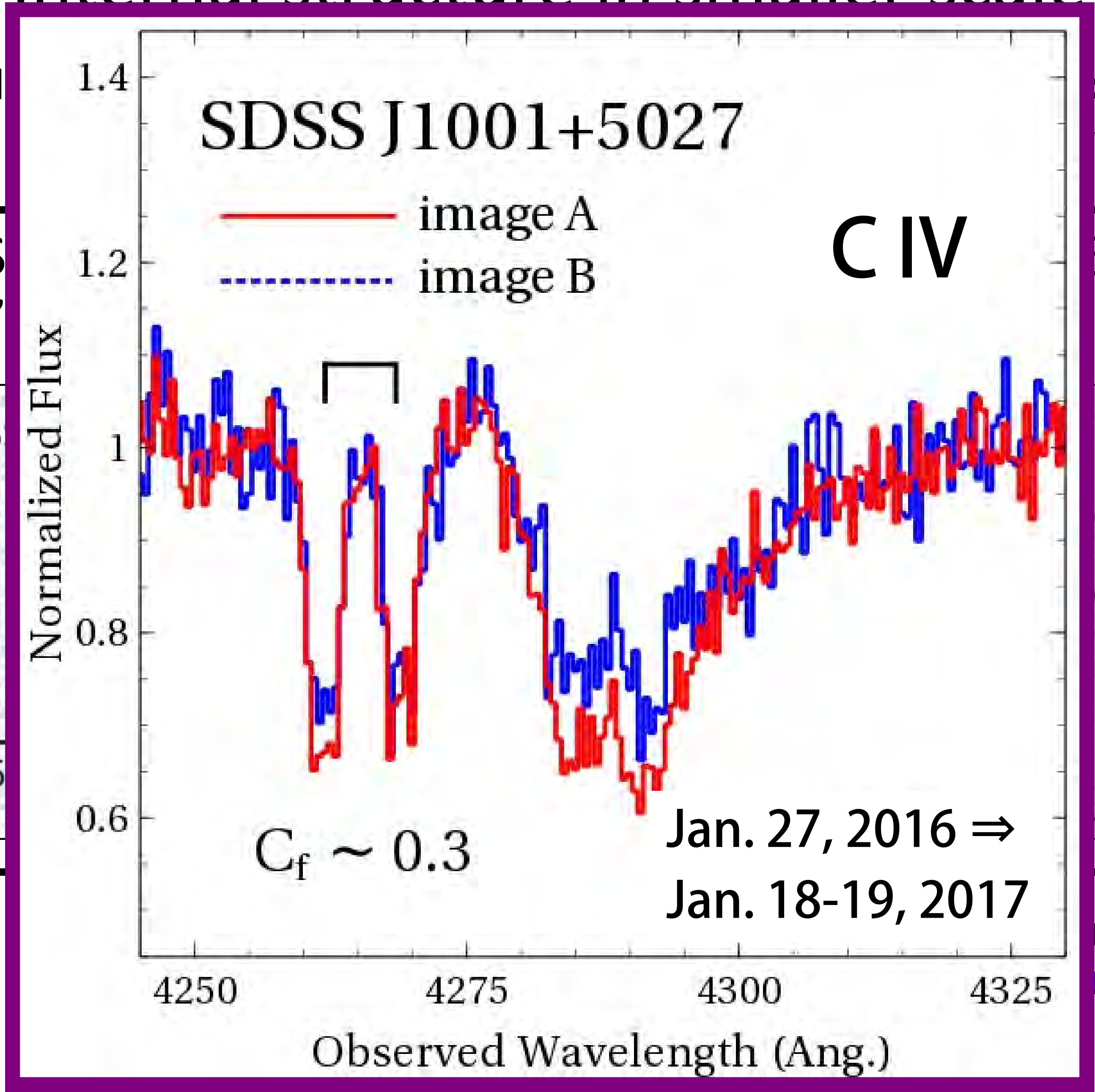
Future Work

Internal structure in smaller scale

We wil... ...bserving lensed ... ...alaxies.

SDS... θ~2"

...623 4".6



SUMMARY

- Gravitationally lensed quasars are powerful tool for investigating the internal structure of quasar outflow through multi-sightline observations.
- We monitored the images A and B of a lensed quasar SDSS J1029+2623 at z_{em}~2.197 whose separation angle (~22".5) is the current record-holder.
- We confirmed our sightlines go through different regions of the outflow.
- A broad PAL absorber has a larger scale than the background flux source (the BELR), while the sizes of narrow PAL absorber and intrinsic NAL absorbers are smaller than that (the BELR or the continuum source).
- Both broad and narrow PAL absorbers locate at <620pc, while intrinsic NAL absorbers locate farther than that.
- About 10 times finer internal structure can be examined by performing the same observation for quasars lensed by a single massive galaxy.